

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. <b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</b>					
1. REPORT DATE		2. REPORT TYPE Viewgraphs		3. DATES COVERED	
4. TITLE AND SUBTITLE  Lateral Heat Flow Effects on Thermographic Sensitivity				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)  Ignacio Perez Paul Kulowitch				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)  Naval Air Warfare Center Aircraft Division 22347 Cedar Point Road, Unit #6 Patuxent River, Maryland 20670-1161				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT  Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT  SAR	18. NUMBER OF PAGES  19	19a. NAME OF RESPONSIBLE PERSON
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (include area code)

Standard Form 298 (Rev. 8-98)  
Prescribed by ANSI Std. Z39-18

DTIC QUALITY INSPECTED 4

20001012 103

# LATERAL HEAT FLOW EFFECTS ON THERMOGRAPHIC SENSITIVITY

Ignacio Perez, Paul Kulowitch  
NAVAL AIR WARFARE CENTER  
AIRCRAFT DIVISION, PATUXENT RIVER, MD

THE SECOND JOINT NASA/FAA/DoD  
CONFERENCE ON AGING AIRCRAFT

August 31 - September 3, 1998

Williamsburg Marriott Hotel  
Williamsburg VA

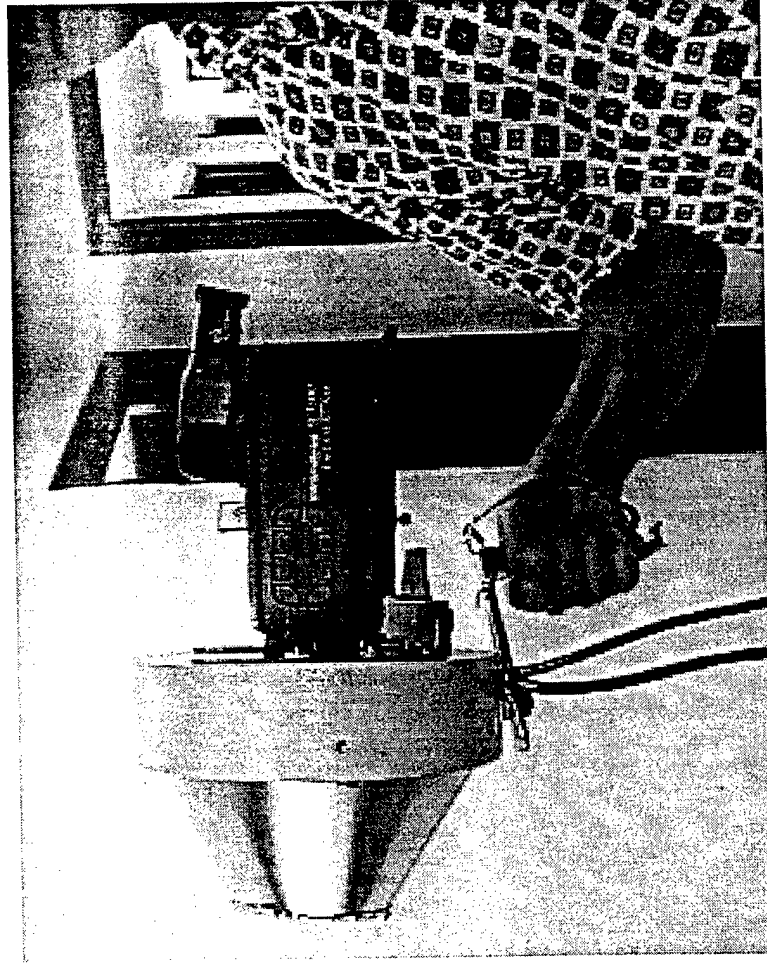
CLEARED FOR  
OPEN PUBLICATION

AUG 20 1998

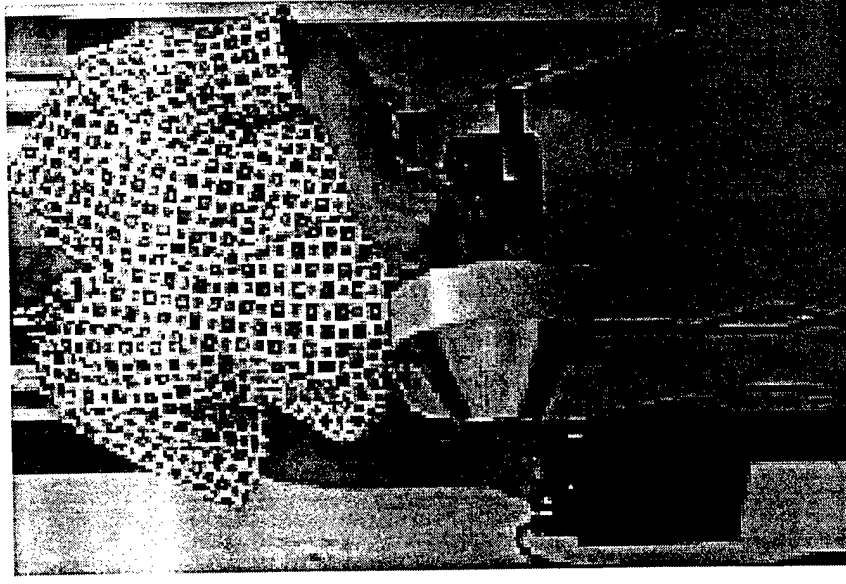
PUBLIC AFFAIRS OFFICE  
NAVAL AIR SYSTEMS COMMAND

*H. Howard*

# PORTABLE IR CAMERA SYSTEM

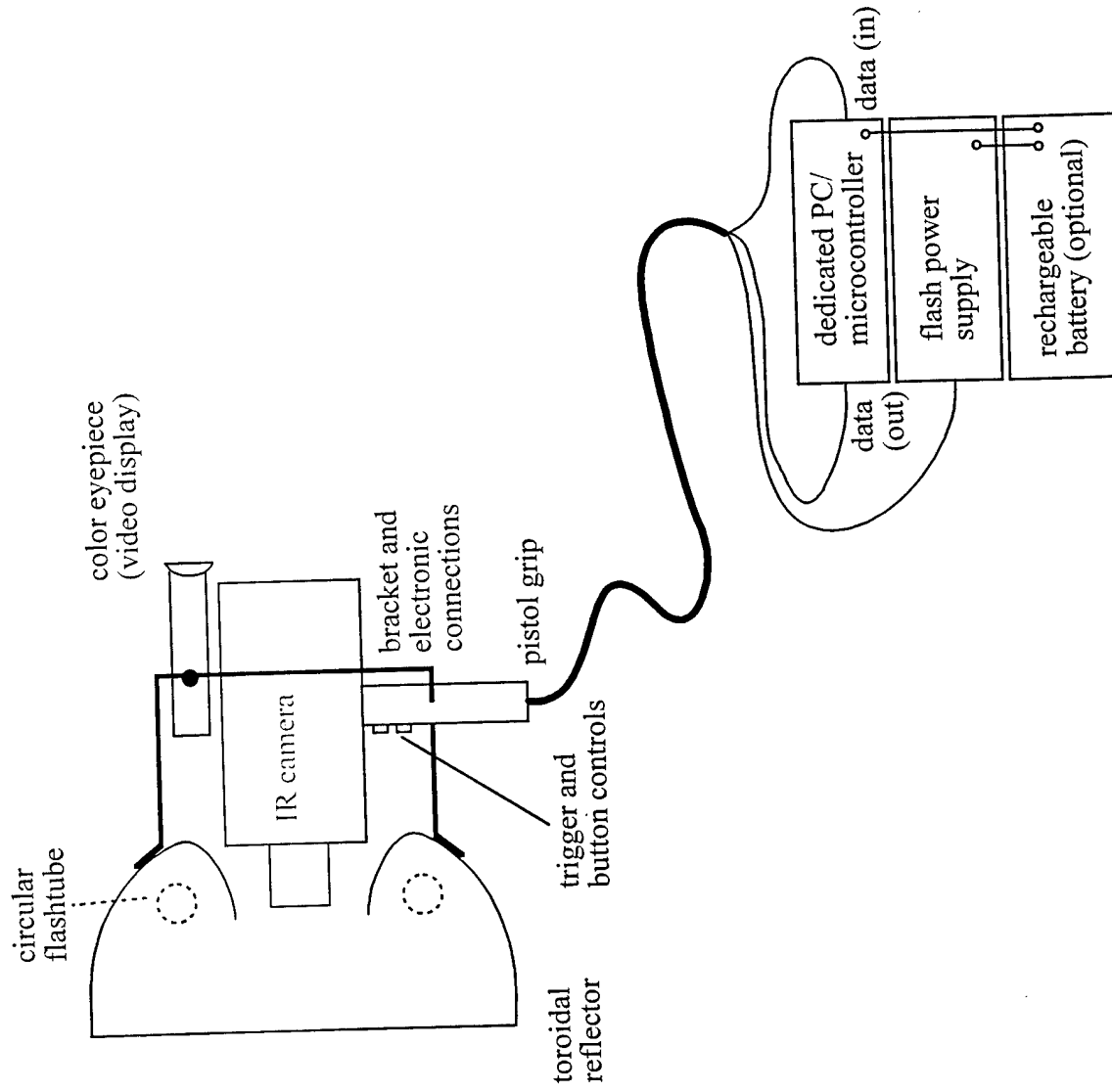


CAMERA HEAD

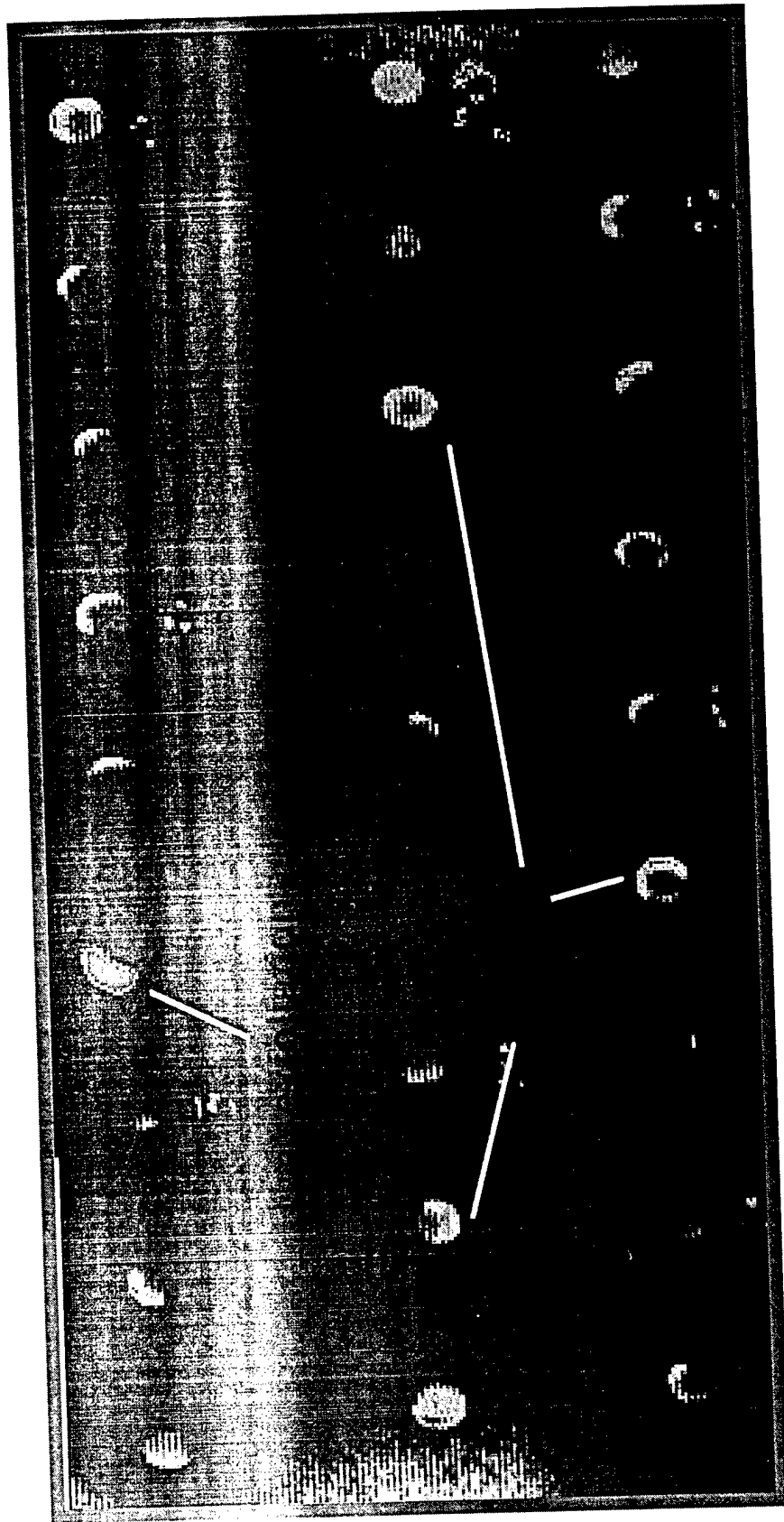


AND POWER SUPPLY

# PORTABLE IR CAMERA SYSTEM

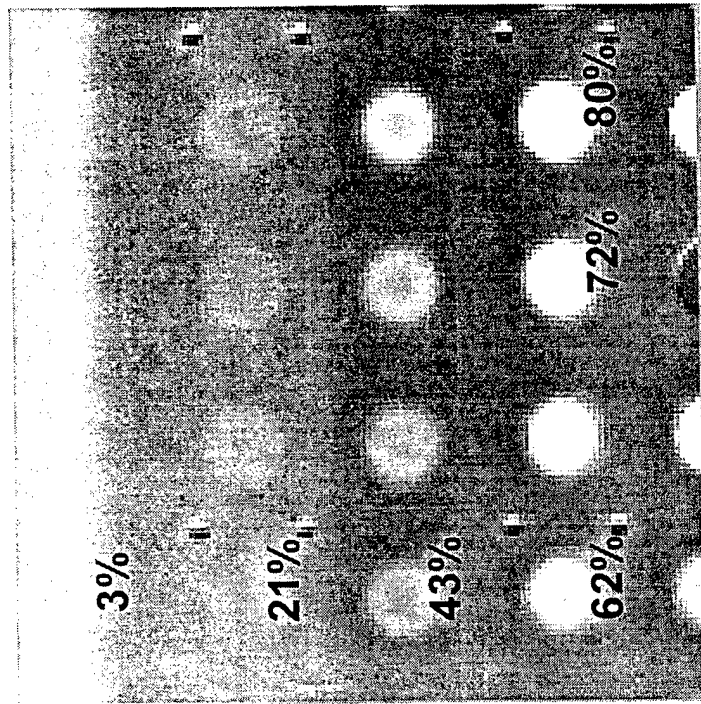


# CORROSION DETECTION



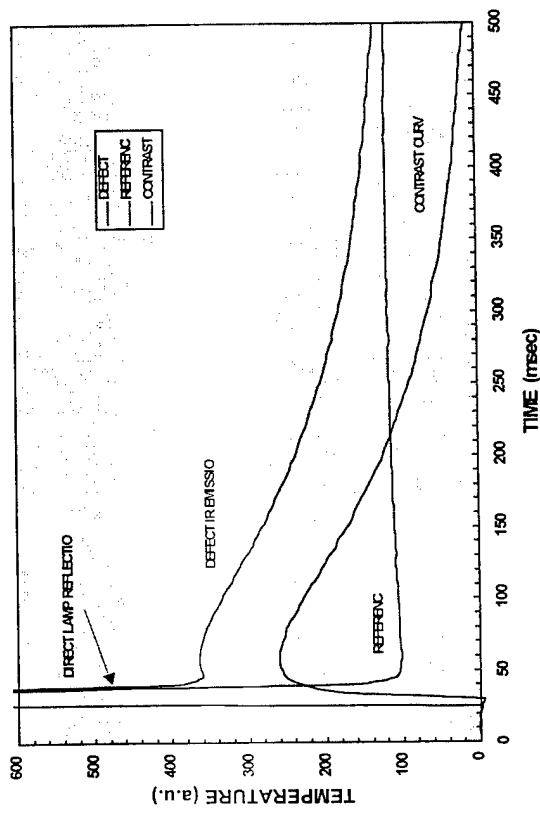
# TEST PANEL & TYPICAL TIME-RESPONSE CURVES

1/8" Thick Al-7075 panel

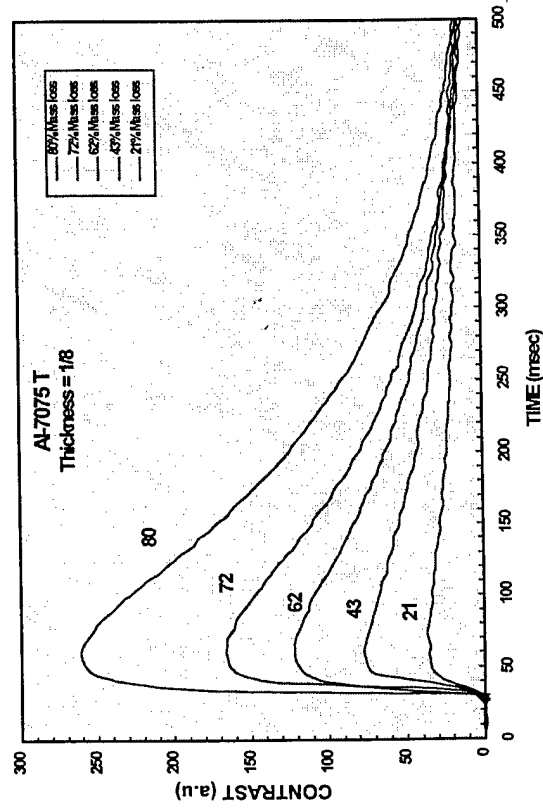


1" Diameter Holes

TEMPERATURE TIME SEQUENCE



CONTRAST CURVE

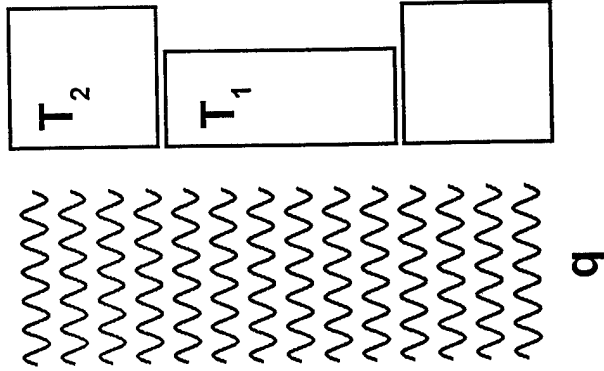
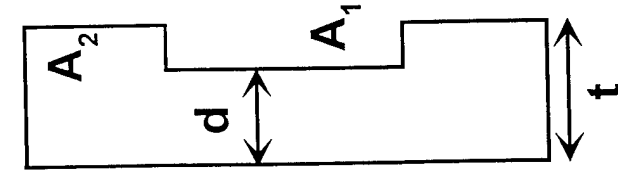


# NO LATERAL HEAT CONDUCTIVITY APPROXIMATION

FLAT  
BOTTOM  
HOLE

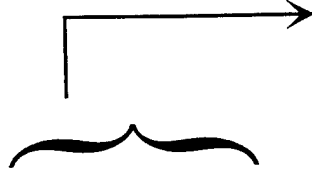
NO LATERAL  
CONDUCTION  
APPROXIMATION

$$q = m \cdot c \cdot \Delta T$$



$$q_2 = \rho \cdot A_2 \cdot t \cdot c \cdot T_2$$

$$q_1 = \rho \cdot A_1 \cdot d \cdot c \cdot T_1$$



$$\Delta T = \frac{Q}{\rho \cdot c} \left( \frac{1}{d} - \frac{1}{t} \right)$$

$$\Delta T = T_1 - T_2$$

$$Q = q/A$$

## CONTRAST PROPERTIES

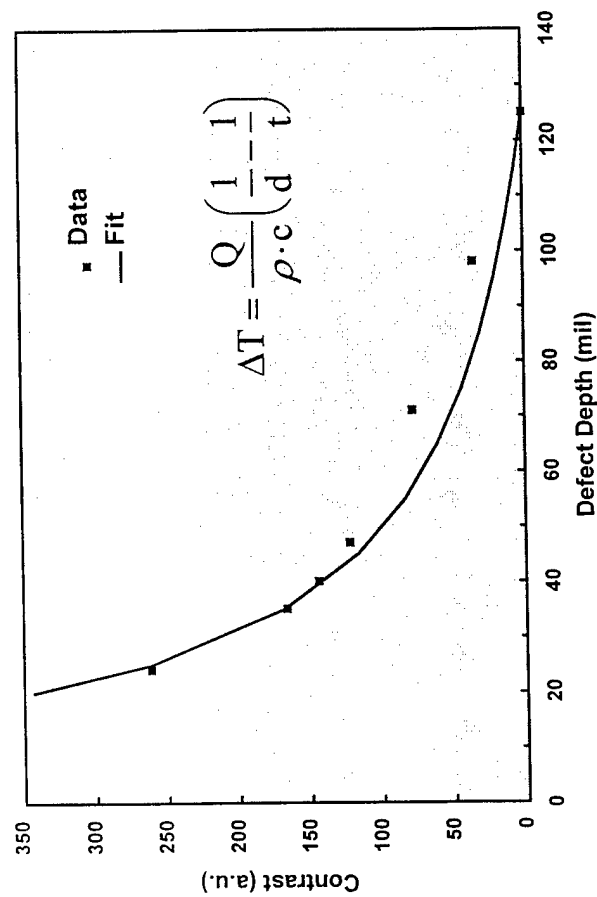
$$\Delta T = \frac{Q}{\rho \cdot c} \left( \frac{1}{d} - \frac{1}{t} \right)$$

1. THE CONTRAST ( $\Delta T$ ) INCREASES LINEARLY WITH THE AMOUNT OF DEPOSITED ENERGY PER UNIT AREA ( $Q$ ).
2. THE HIGHER THE SPECIFIC HEAT-DENSITY OF A MATERIAL ( $\rho c \uparrow$ ) THE SMALLER THE PEAK CONTRAST ( $\Delta T \downarrow$ )
3. THE CLOSER THE DEFECT TO THE SURFACE ( $d \rightarrow 0$ ) THE HIGHER THE PEAK CONTRAST ( $\Delta T \rightarrow \infty$ ).
4. AS THE DEFECT DEPTH APPROACHES THE PANEL THICKNESS ( $d \rightarrow t$ ) THE CONTRAST VANISHES ( $\Delta T \rightarrow 0$ ).
5. FOR A GIVEN DEFECT DEPTH  $D$ , THE THICKER THE PANEL ( $t \rightarrow \infty$ ) THE LARGER THE CONTRAST ( $\Delta T \rightarrow Q/\rho c d$ ).

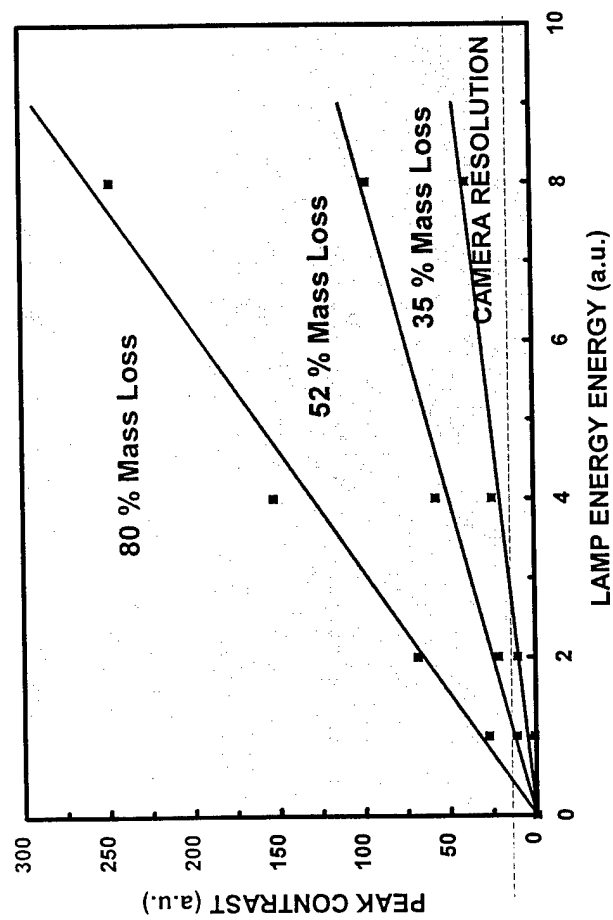


# SIMPLE MODEL CORRELATION (no lateral heat flow)

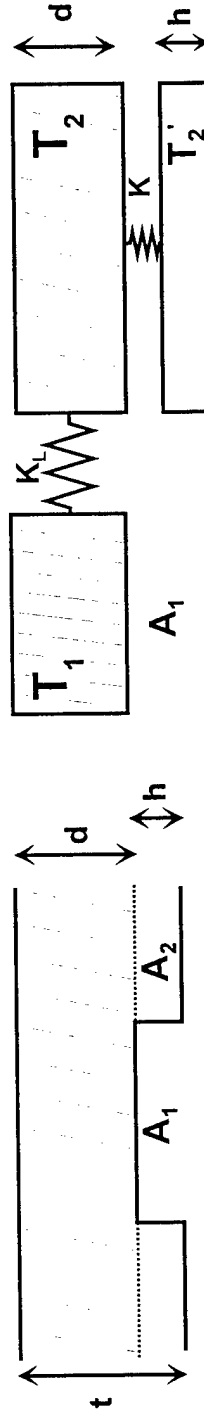
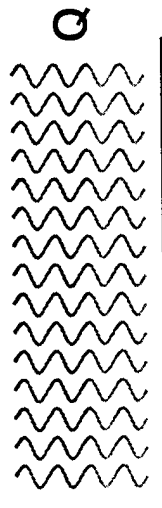
CONTRAST vs DEPTH



DEPTH OF RESOLUTION vs ENERGY



# LATERAL HEAT FLOW MODEL



$$\rho \cdot A_1 \cdot d \cdot c \cdot \frac{dT_1}{dt} = k_L \cdot \frac{A_L}{R} (T_2 - T_1)$$

$$\rho \cdot A_2 \cdot d \cdot c \cdot \frac{dT_2}{dt} = k_L \cdot \frac{A_L}{R} (T_1 - T_2) + k \cdot \frac{A_2}{d+h} (T_2' - T_2)$$

$$\rho \cdot A_2 \cdot h \cdot c \cdot \frac{dT_2'}{dt} = k \cdot \frac{A_2}{d+h} (T_2 - T_2')$$

$k$  = Thermal Conductivity

$k_L$  = Lateral Thermal Conductivity

# LATERAL HEAT FLOW EFFECTS

$$\Delta T(t) = \frac{Q}{\rho c \cdot d \cdot (1 - a + r)} \left( e^{-\frac{a}{d(d+h)} \rho c t} - e^{-\frac{l+r}{d(d+h)} \rho c t} \right)$$

$$t_{\max} = \frac{\rho c}{k} \frac{d \cdot t_o}{1 - a + r} \ln \frac{1+r}{a}$$

$$\Delta T_{\max} = \frac{Q}{\rho c} \left( \frac{1}{d} - \frac{1}{t_o} \right) \cdot \left( \frac{a \cdot h}{t_o} \right)^{\frac{1}{\frac{t_o}{a \cdot h} - 1}}$$

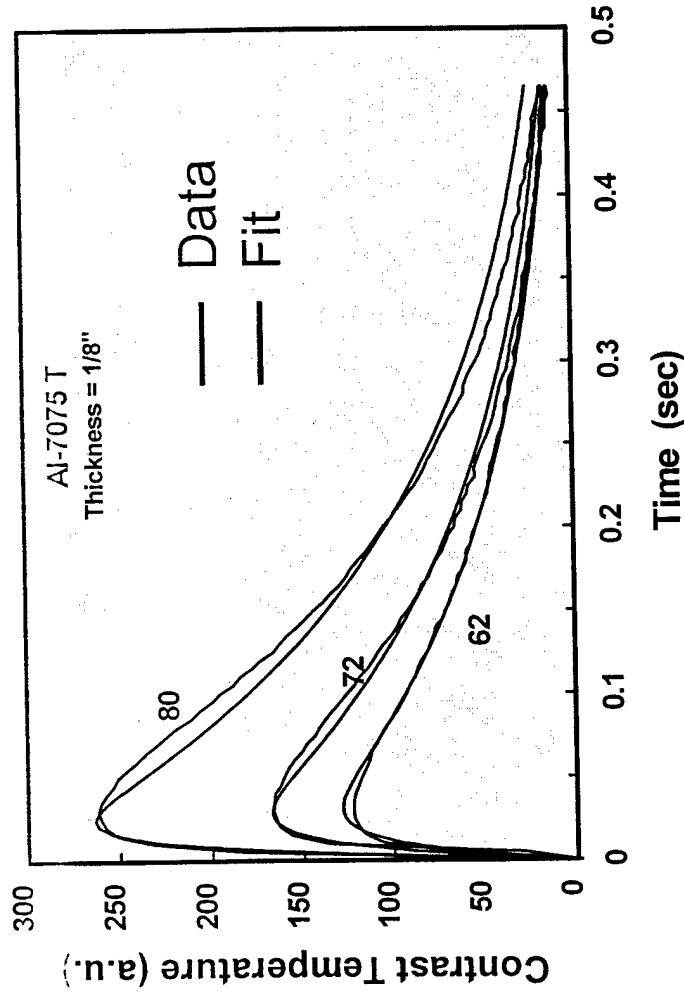
$$a = \frac{k_L}{k} \frac{A_L}{A} \frac{d+h}{R}$$

$$r = \frac{d}{h}$$

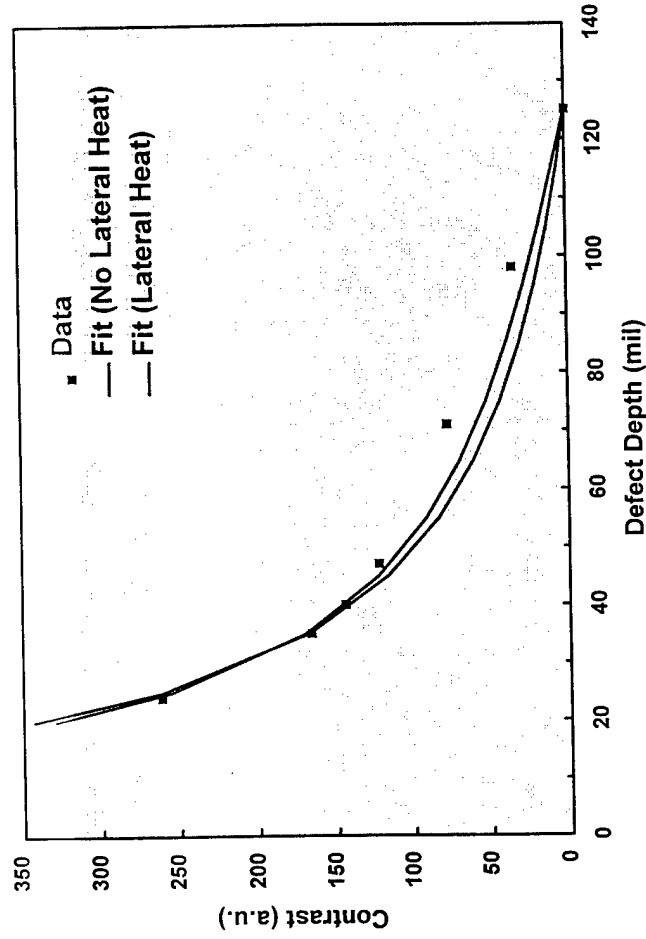
**LATERAL HEAT  
 FACTOR**

# THERMAL CONTRAST PREDICATIONS

Fit of Contrasts Curves



CONTRAST vs DEPTH



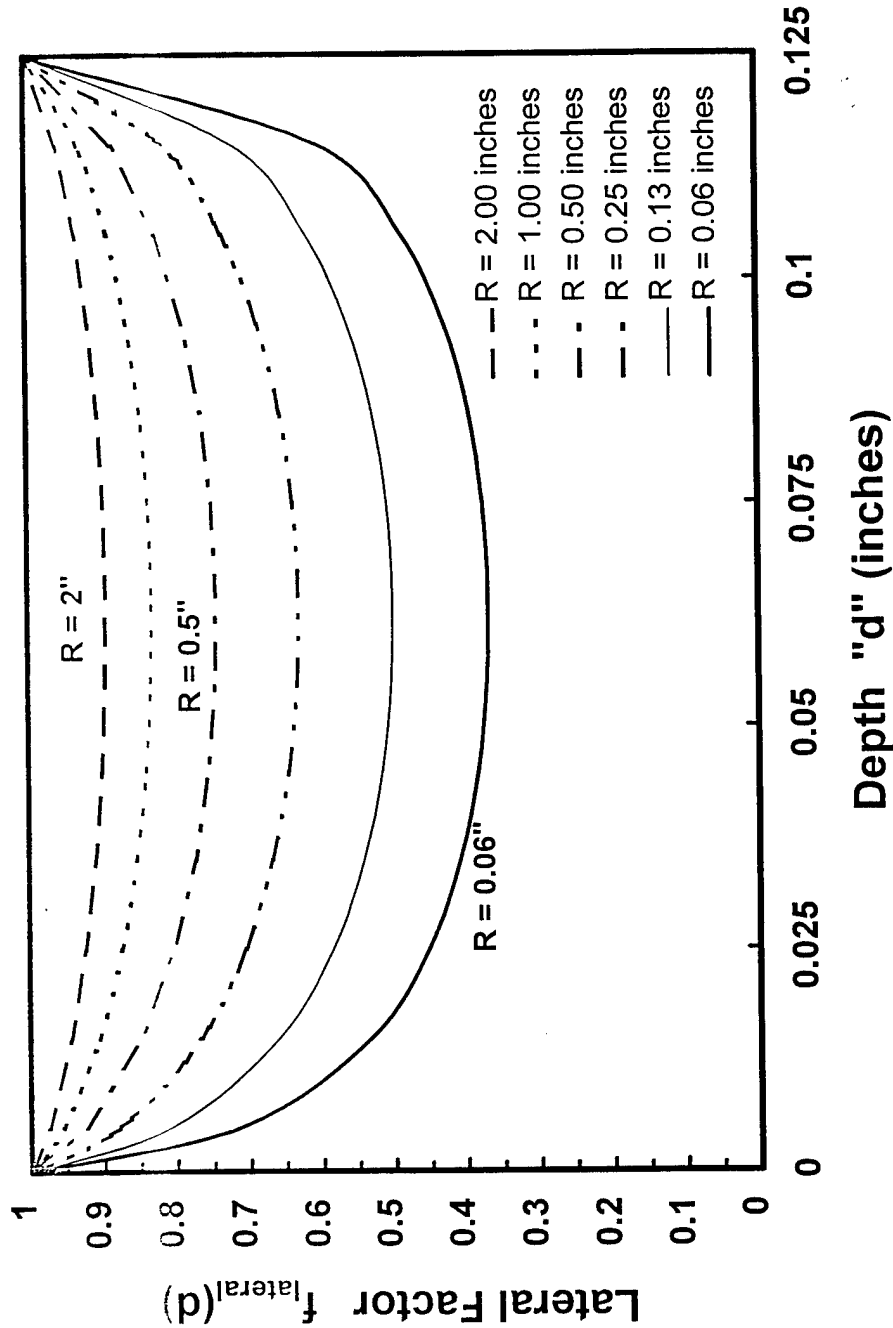
$$\Delta T(t) = \frac{Q}{\rho c \cdot d \cdot (1 - a + r)} \left( e^{-\frac{a}{d(d+h)} \rho c t} - e^{-\frac{1+r}{d(d+h)} \frac{k}{\rho c} t} \right)$$

$$\Delta T_{\max} = \frac{Q}{\rho c} \left( \frac{1}{d} - \frac{1}{t_o} \right) \cdot \left( \frac{a \cdot h}{t_o} \right)^{\frac{1}{\frac{t_o}{a \cdot h} - 1}}$$

# LATERAL HEAT FACTOR

(effective contact conductivity model)

## Lateral Heat Factor



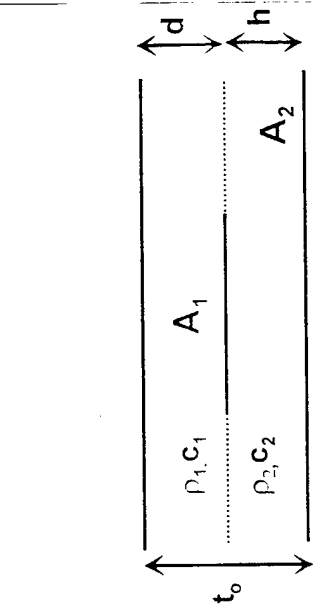
$$\Delta T_{max} = \frac{Q}{\rho c} \left( \frac{1}{d} - \frac{1}{t_o} \right) \cdot \left( \frac{a \cdot h}{t_o} \right)^{\frac{1}{\frac{t_o}{a \cdot h} - 1}}$$



# OTHER MODELING RESULTS



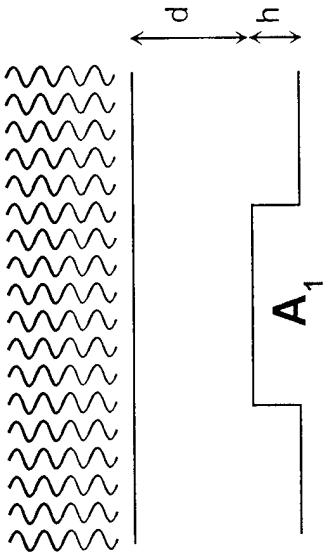
$$Q = J \cdot A \cdot t$$



$$\Delta T(t) = \frac{Q}{\rho_1 c_1} \cdot \frac{r_1}{d(r_1 + b \cdot r_1 t_2 - a_1)} \cdot \left( e^{-\frac{a_1}{Rd} \frac{k}{\rho_1 c_1} t} - e^{-\frac{r_1(1+br_2)}{Rd} \frac{k}{\rho_1 c_1} t} \right)$$

$$\Delta T_{\text{peak}} = Q \cdot \left( \frac{1}{d} - \frac{1}{t_o} \right) \frac{\rho_2 c_2}{\rho_1 c_1} \frac{d+h}{d\rho_1 c_1 + h\rho_2 c_2} \cdot \left[ \frac{a_1}{r_1(1+br_2)} \right]^{1-\frac{a_1}{r_1(1+br_2)}}$$

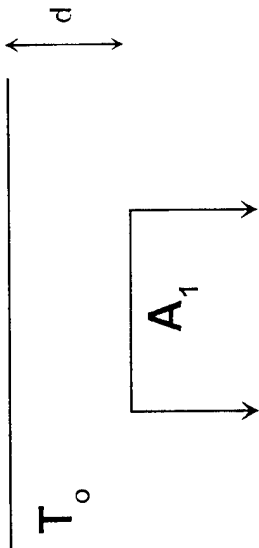
$$a_1 = \frac{k_L}{k} \frac{A_d}{A} \quad a_2 = \frac{k_L}{k} \frac{A_h}{A} \quad r_1 = \frac{R}{d+h} \quad r_2 = \frac{d}{h} \quad b = \frac{\rho_1 c_1}{\rho_2 c_2}$$



$$\Delta T(t) = \frac{J}{a \cdot k} \frac{d+h}{(1+r)(1+r-a)} \cdot \left( e^{-\frac{a}{d(d+h)} \frac{k}{\rho c} t} - a(1-e^{-\frac{1+r}{d(d+h)} \frac{k}{\rho c} t}) \right)$$

$$\Delta T(t \rightarrow \infty) = \frac{J}{a \cdot k} \cdot h$$

$$a = \frac{k_L}{k} \frac{A_L}{A} \frac{d+h}{R} \quad r = \frac{d}{h}$$



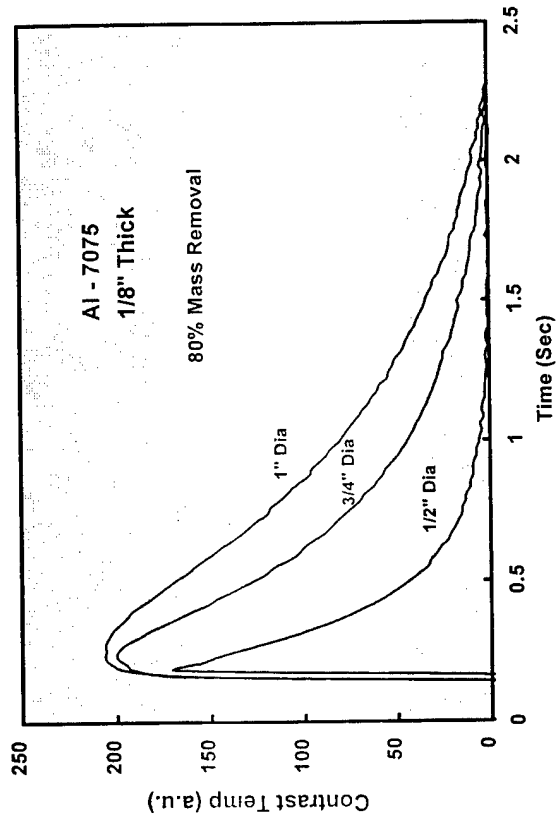
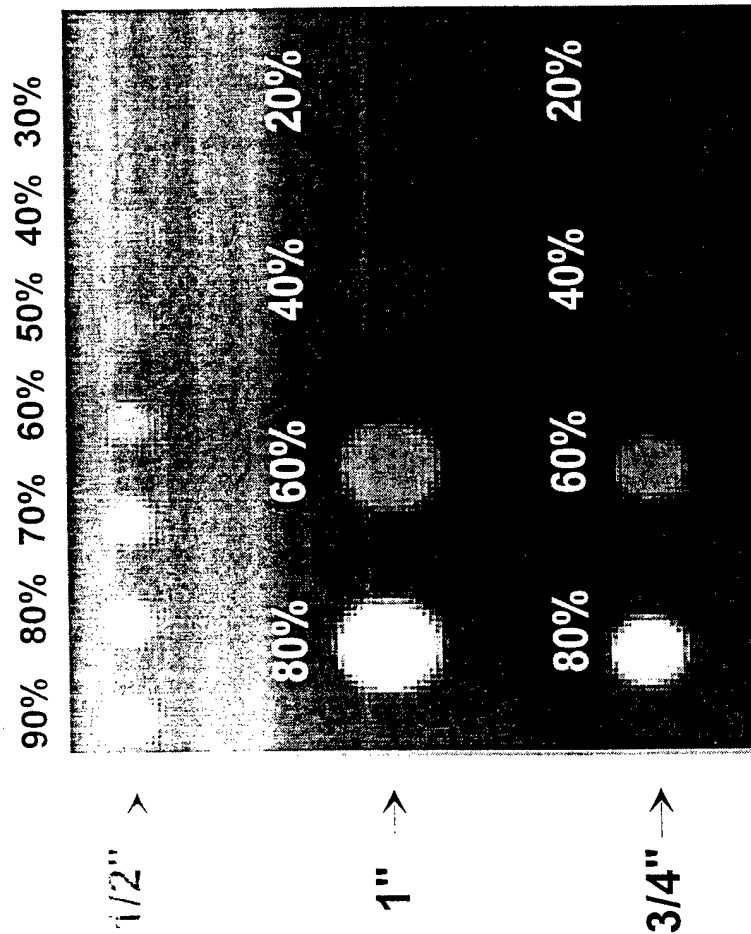
$$\Delta T(t) = \frac{Q}{\rho c} \frac{kR}{d(AkR + A_d k_1 d)} \left( e^{-\frac{b}{d^2} \frac{k}{\rho c} t} - e^{-\frac{1}{d^2} \frac{k}{\rho c} t} \right)$$

$$\Delta T_{\text{peak}} = \frac{Q}{\rho c} \frac{kR(b-1)}{d(dA_d k_1 + RAk)} \cdot [b]^{1-b}$$

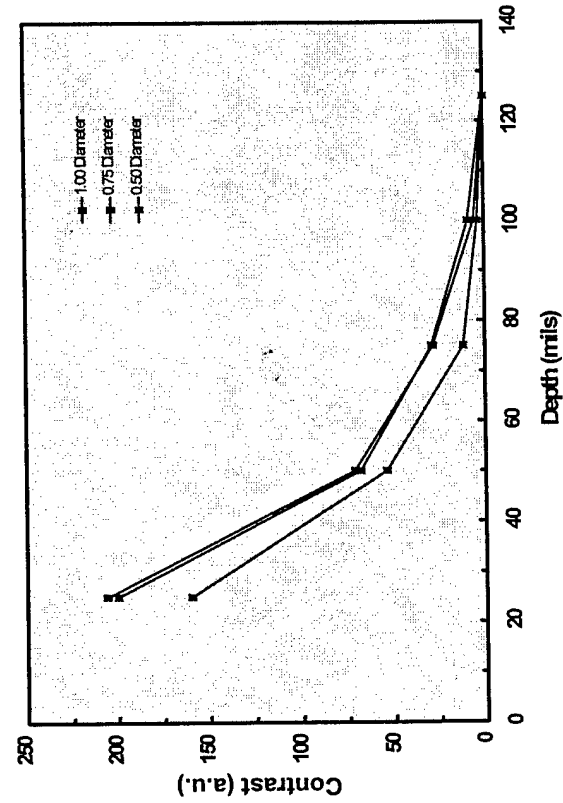
$$t_{\text{peak}} = \frac{\rho c}{k} \frac{d^2}{b-1} \ln b$$

$$b = \frac{k_1}{k} \frac{A_d}{A_1} \frac{d}{R}$$

# EXPERIMENTAL DATA (80% mass removal)



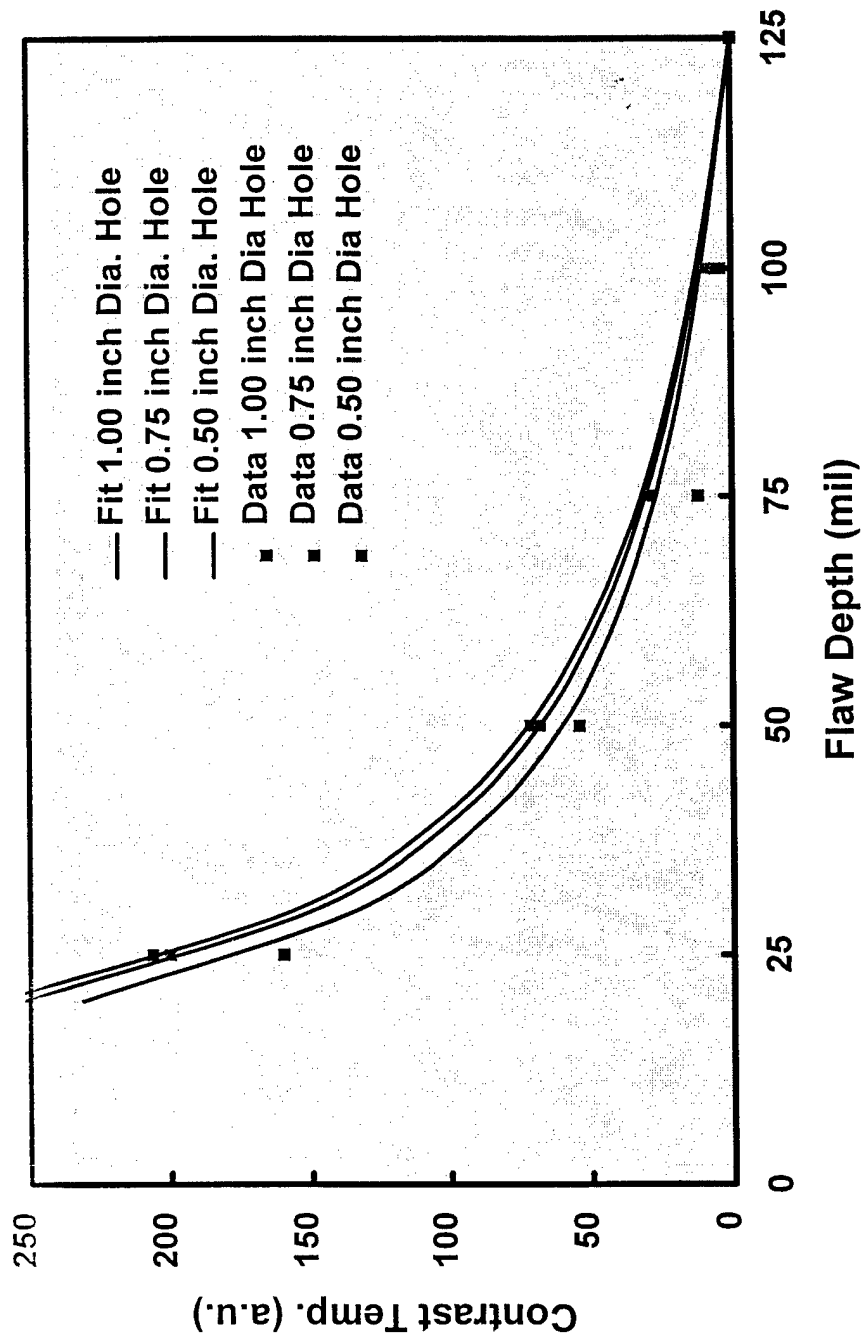
PEAK TEMP. vs DEPT



# MODEL CORRELATION (effects of defect size)

$$\Delta T_{\max} = \frac{Q}{\rho c} \left( \frac{1}{d} - \frac{1}{t_o} \right) \cdot \left( \frac{a \cdot h}{t_o} \right)^{\frac{1}{\frac{t_o}{a \cdot h} - 1}}$$

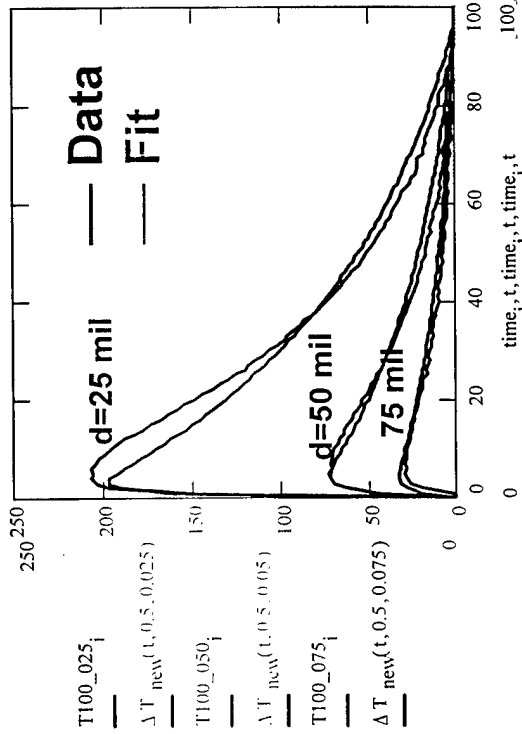
Effects of Radii



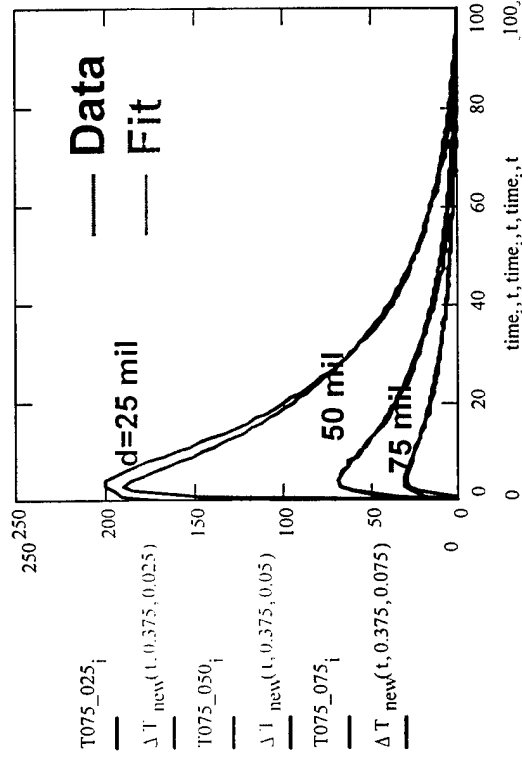


# MODEL TIME-RESPONSE PREDICTIONS (varying defect sizes and locations)

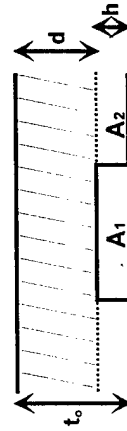
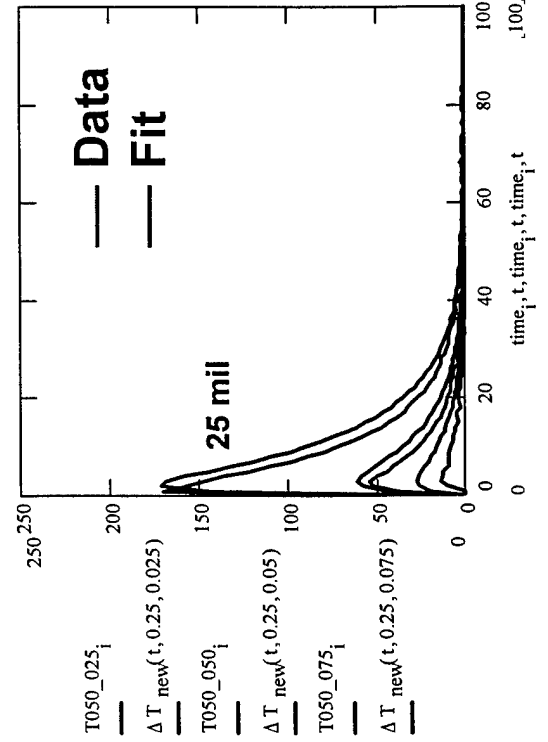
Dia = 1.00"



Dia = 0.75"



Dia = 0.50"



$$\Delta T(t) = \frac{Q}{\rho_c \cdot d \cdot (1 - a + r)} \times \left( e^{-\frac{a}{d(d+h)} \rho_c t} - e^{-\frac{l+r}{d(d+h)} \rho_c t} \right)$$

# GRAPHITE EPOXY COMPOSITE PANEL

**t = 117 mil**

**d = 48 mil**

**d = 61 mil**



← **1/2" dia**

**31 mil**

**41 mil**

**52 mil**

**62 mil**



← **1/4" dia**

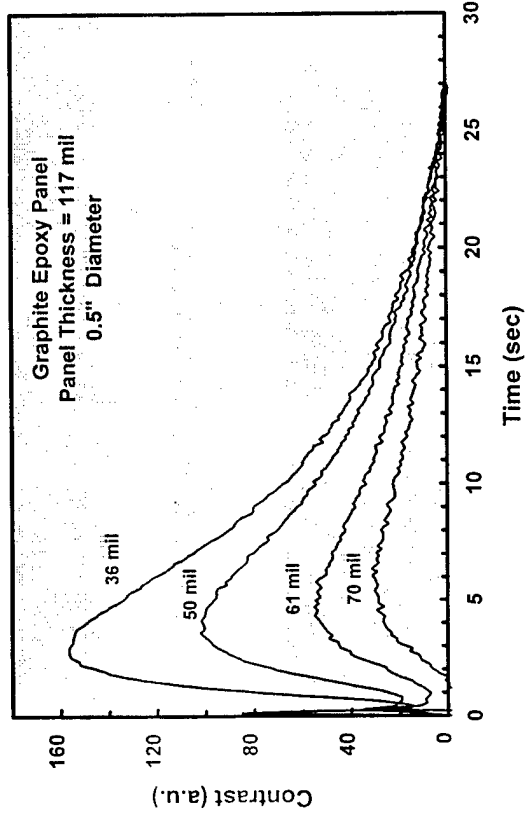
**d = 36 mil**

**d = 70 mil**

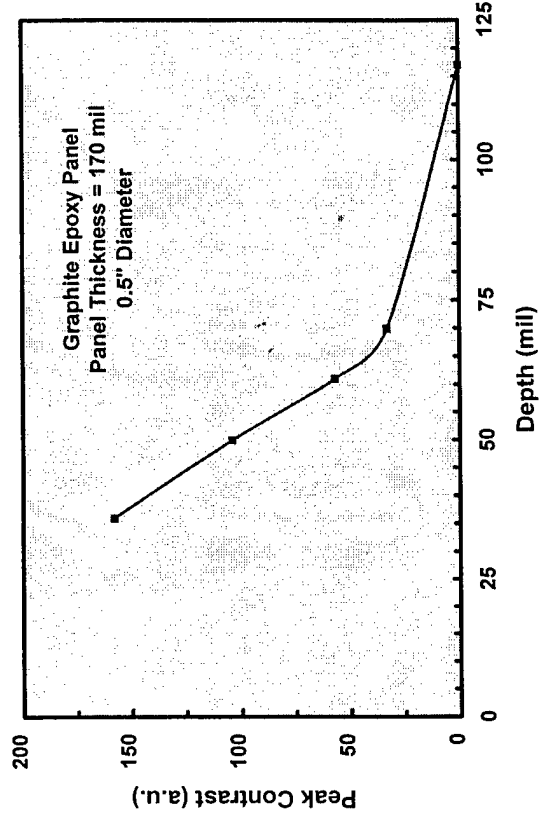


← **1/2" dia**

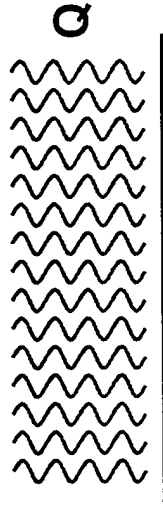
**CONTRAST vs TIME**



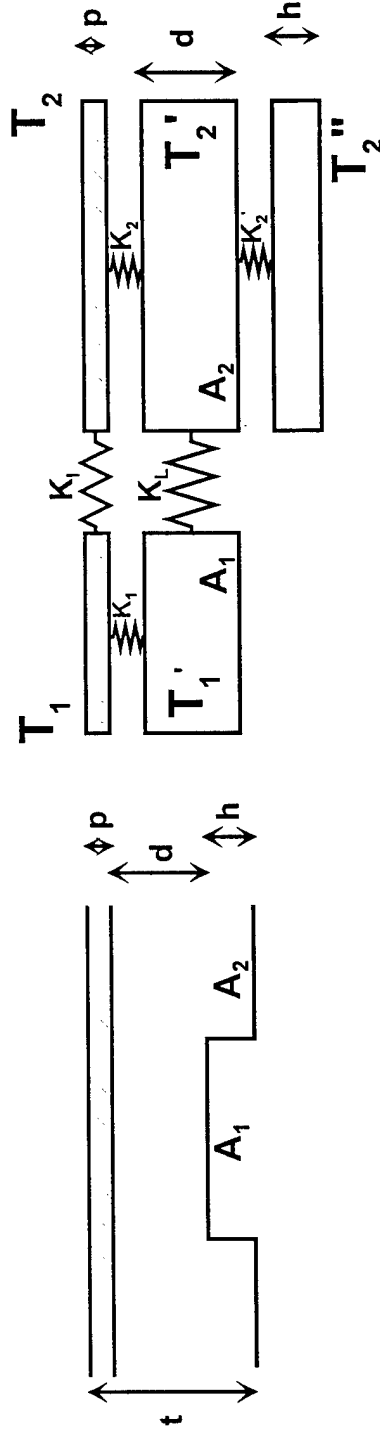
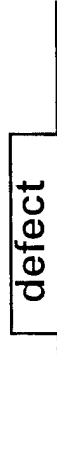
**PEAK CONTRAST vs DEPTH**



# SIMPLE FINITE ELEMENT APPROXIMATION



Sample



$$\rho \cdot A_1 \cdot p \cdot c \cdot \frac{dT_1}{dt} = k \cdot A_1 (T_1' - T_1) + k_L \cdot A_p (T_2 - T_1)$$

$$\rho \cdot A_2 \cdot p \cdot c \cdot \frac{dT_2}{dt} = k \cdot A_2 (T_2' - T_2) + k_L \cdot A_p (T_1 - T_2)$$

...

$$\rho \cdot A_2 \cdot h \cdot c \cdot \frac{dT_2''}{dt} = k \cdot A_2 (T_2' - T_2'')$$

$k$  = Effective Contact Normal Thermal Conductivity

$k_L$  = Effective Contact Lateral Thermal Conductivity

# FITTING RESULTS

## GRAPHITE EPOXY COMPOSITE

117 mil Thick

